

UNITED STATES PATENT APPLICATION

TITLE:

PLANETARY-HARMONIC MOTOR

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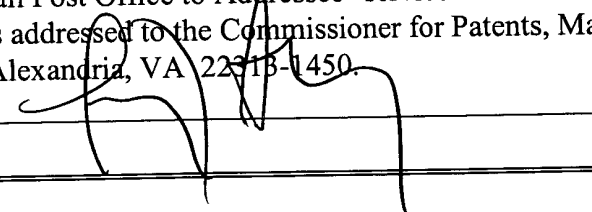
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PLANETARY-HARMONIC MOTOR

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Patent Application No. 60/411,906, filed September 19, 2002 by Dan Stoianovici and Louis R. Kavoussi.

STATEMENT AS TO FEDERALLY SPONSORED RESEARCH

This invention was made with Government support under Grant No. 1 R21 CA88232-01A1 and entitled "Multi-Imager Compatible Robot For Prostrate Access," which was awarded by the National Institute of Health. The Government may have certain rights in this invention.

BACKGROUND OF THE INVENTION

1. FIELD OF THE INVENTION

This invention relates to motors that provide rotary motion. More particularly, one embodiment of the present invention relates to a motor which is constructed from materials that can be used in all classes of medical imaging

1 equipment and that generates precise, high torque, backlash-free rotary motion
2 without using electricity.

3 4 5 2. DESCRIPTION OF PRIOR ART

6 Noninvasive, diagnostic imaging techniques, such as ultrasound, x-ray and
7 magnetic resonance imaging (MRI) are widely used in medicine. They are used to
8 produce cross-sectional images of a patient's organs and other internal body
9 structures.

10 MRI typically involves the patient lying inside a large, hollow cylinder
11 containing a strong electromagnet, which generates a strong and uniform magnetic
12 field that causes the electrons in a patient's body to spin in a uniform and predictable
13 manner. The MRI equipment can then manipulate the spinning electrons and use the
14 resulting information to generate an image of the inside of a patient's body.

15 However, difficulties are encountered in obtaining accurate images when
16 disruptions and deflections in the magnetic field are experienced due to the presence
17 in the field of materials that produce a magnetic field and/or are susceptible to
18 producing their own magnetic fields when placed within an external magnetic field.

19 One source of magnetic field distortion can be equipment such as motors that
20 are in the vicinity of the MRI machine. Motors are generally formed with materials
21 that produce a magnetic field. Examples of such materials that are commonly used in
22 motors include iron and brass. Thus, when placed in the field generated by the MRI
23 machine, the motors can cause artifacts in the image of the patient's body.

24 Other forms of medical imaging (e.g., x-ray and ultrasound imagers) are also
25 seen to have similar problems of distortions in their output images due to the presence
26 of motors in the vicinity of the imaging equipment.

27 Prior attempts to provide a motor that can be used in such imaging
28 environments have involved the use of piezoelectric elements to provide the motor's
29 power. See U.S. Patent Nos. 5,233,257 and 6,274,965.

30 Despite these efforts, there still exists a need for improved motors that can be
31 placed near medical imaging equipment with minimal risk of creating artifacts.

1 There is a related need for a motor that does not produce a magnetic field. There is
2 yet another need for a motor that has a low susceptibility of being induced to produce
3 a magnetic field. Additionally, there is a need for a rotary motor of the type that is
4 not powered by electricity.

5 6 3. OBJECTS AND ADVANTAGES

7 There has been summarized above, rather broadly, the prior art that is related
8 to the present invention in order that the context of the present invention may be
9 better understood and appreciated. In this regard, it is instructive to also consider the
10 objects and advantages of the present invention.

11 It is an object of the present invention to provide a rotary motor that can be
12 used for medical applications which require the motor to be located in or in close
13 proximity to medical imaging equipment.

14 It is another object of the present invention to provide a rotary motor that can
15 be used in a surgical environment.

16 It is yet another object of the present invention to provide a motor that can
17 provide precise, high torque, backlash-free rotary motion.

18 It is still another object of the present invention to provide a rotary motor that
19 does not utilize electrical power or electrical components for operation.

20 It is a further object of the present invention to provide a precise rotary motor
21 whose motion can be monitored by sensors located at a site that is distant from the
22 location of the motor itself.

23 It is an object of the present invention to provide a rotary motor that can be
24 powered by other than electrical means.

25 These and other objects and advantages of the present invention will become
26 readily apparent as the invention is better understood by reference to the accompanying
27 summary, drawings and the detailed description that follows.

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SUMMARY OF THE INVENTION

Recognizing the medical needs for the development of a precise rotary motor that can be used in medical imaging environments, the present invention is generally directed to satisfying the needs set forth above. In accordance with the present invention, the foregoing need can be satisfied by providing an especially designed motor that is suitable for use in a medical imaging room.

In a preferred embodiment, such a motor has: (a) a centrally located means for actuating a radial wave, (b) a deformable flexspline having an inner surface and a toothed outer surface, with the flexspline coaxially aligned with the central axis of the radial wave actuating means and oriented such that the flexspline inner surface is proximate the outer boundary surface of the actuation means, and with the flexspline toothed outer surface having a first specified number of teeth, (c) a circular spline having a toothed inner surface, the spline having an outer boundary surface and being coaxially aligned with the central axis and oriented such that the spline toothed inner surface is proximate the flexspline's toothed outer surface, with the spline inner surface having a second specified number of teeth which is different than the first specified number of teeth in the flexspline, wherein the actuation means is operable so that the action of its radial wave causes at least one of the flexspline teeth to engage at a point the toothed side of the circular spline in such a manner that an engagement point passes as a wave around the inner perimeter of the circular spline, with the movement of this engagement point causing the flexspline to rotate around its central axis.

In a preferred embodiment, this radial wave actuating means has: (a) a central ring having an outer, boundary surface and a center point, (b) a plurality of diaphragm pistons, each having a fluid containing cavity, (c) a diaphragm that covers each piston's and top action surface, with these pistons being mounted along the perimeter of the ring's boundary surface so that their action surfaces move radially as the amount of fluid in the cavities is increased, (d) a coaxially aligned planetary gear having an inner surface and a toothed outer surface with a first specified number of

1 teeth, (e) a wave generator gear having an outer surface and a toothed inner surface
2 and oriented such that the wave generator toothed inner surface is proximate the
3 planetary gear's toothed outer surface, with the wave generator gear having a second,
4 specified number of teeth which is different than the planetary gear's first specified
5 number of teeth, and (f) a ring bearing whose inner surface is proximate the wave
6 generator gear outer surface.

7 In another preferred embodiment, such a motor has: (a) a central ring, (b) a
8 plurality of diaphragm pistons, each having a fluid containing cavity, a diaphragm that
9 covers the cavity and a top action surface, with the pistons being mounted along the
10 perimeter of the ring boundary surface and configured so that their action surfaces
11 move radially from the ring's center point as the amount of fluid in the cavities is
12 increased, (c) a coaxially aligned planetary gear having an inner surface and a toothed
13 outer surface with a first specified number of teeth, (d) a coaxially aligned inner gear
14 having an outer surface and a toothed inner surface and oriented such that the inner
15 gear's toothed surface is proximate the planetary gear's toothed surface, with the
16 inner gear having a second, specified number of teeth which is different than the first
17 specified number of teeth in the planetary gear, and (e) a ring bearing whose inner
18 surface is proximate the inner gear outer surface, wherein by a specified flow of fluid
19 through the pistons the planetary gear is caused to move relative to the ring center
20 point so that a portion of the planetary gear outer surface contacts the inner surface of
21 the inner gear in such a manner that at least one of the planetary gear teeth engages at
22 a point the toothed side of the inner gear in such a manner that the engagement point
23 passes as a wave around the inner perimeter of the inner gear, this movement of the
24 engagement point causing the inner gear to rotate around the ring center point.

25 Thus, there has been summarized above, rather broadly, the present invention
26 in order that the detailed description that follows may be better understood and
27 appreciated. There are, of course, additional features of the invention that will be
28 described hereinafter and which will form the subject matter of any eventual claims to
29 this invention.
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BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A and 1B illustrate the operation of a pair of coupled hydraulic cylinders for remotely actuating a linear motion.

FIG. 2 illustrates the operation of three sets of coupled hydraulic cylinders for remotely actuating a rotary motion.

FIGS. 3A and 3B illustrate the use of rollers and a cam bearing for connecting the piston rods of the hydraulic cylinders shown in FIG. 2 with an elliptical drive cam.

FIG. 4 illustrates the components of and principle of operation of a standard harmonic drive gear.

FIG. 5 is a plan view of a preferred embodiment of the harmonic motor of the present invention which utilizes an elliptical bearing or wave generator that is driven by hydraulic cylinders that are sequentially operated.

FIG. 6 is a plan view of a "radial wave actuator" for a preferred embodiment of the present invention, wherein this actuator replaces the elliptical, wave generator of FIG. 5 with sequentially activated pairs of diaphragms that directly deform the flexspline.

FIG. 7 is a plan view of a "tangential wave actuator" for a preferred embodiment of the present invention, wherein this actuator replaces the elliptical wave generator of FIG. 5 with sequentially activated groups of inflatable cylinders that deform a wave generator ring that drives the flexspline.

FIGS. 8A and 8B presents a side view and a cross sectional view of a harmonic planetary motor embodiment of the present invention.

FIG. 9 shows an illustration of the pump that is used to drive a harmonic planetary motor.

FIGS. 10A and 10B presents a side view and a cross sectional view of a planetary motor embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Before explaining at least one embodiment of the present invention in detail, it is to be understood that the invention is not limited in its application to the details of construction and to the arrangements of the components set forth in the following description or illustrated in the drawings. The invention is capable of other embodiments and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting.

In general, the present invention relates to motors that are made with materials that have low magnetic susceptibility and produces minimal, if any, magnetic fields. For example, materials such as plastics, glass, ceramics, rubbers, etc.

The invention of the present invention is based on two principles of transmission: (a) the coupled, fluid actuated pistons or cylinders for supplying linear motion at a remote location, and (b) the harmonic drive transmission for providing extremely precise, zero-backlash speed reduction capabilities.

Two versions of the coupled, fluid actuated pistons are schematically represented in FIG. 1A and 1B. The “double acting” method presented in FIG. 1A includes two cylinders connected port-to-port on their similar sides by two closed circuits. The fluid agent inside these circuits could be either pneumatic or hydraulic. An external force applied on the rod of the “pump cylinder” is transmitted through the compression of the agent into linear force at the piston of the “motor cylinder”, like in the braking system of cars.

The force transmission ratio of the motor – pump cylinder coupling may be expressed as:

$$\text{Force Transmission Ratio} = T = \frac{F_m}{F_p} = \frac{S_M}{S_P} = \frac{S_m}{S_p} \quad \text{Equation 1}$$

where, F_m and F_p are the forces acting on the motor and pump rods respectively, and S_M , S_m , S_P , S_p are the surface areas on the sides of both pistons, as represented in FIG. 1. Scaling may be achieved by using different cylinder sizes for the pump and motor.

Using an incompressible agent (hydraulic actuation case) and considering that the system operates at low pressure levels for which the deformation of the hydraulic circuit is negligible, the displacement ratio may be expressed as the inverse of the force ratio:

$$\frac{x_m}{x_p} = \frac{1}{T} \quad \text{Equation 2}$$

where, x_m and x_p are the displacements of the motor and pump pistons, respectively. Equation 1 also reveals the size constraint of the cylinders in order to match the volumes displaced on both sides of the piston chambers.

The “spring return” principle presented in FIG. 1B is similar but uses a single connection line between the cylinders thus reducing to half the number of conduits required. This can be significant in the case of multiple motors. The back draw is the limitation and variability of force in one direction given by the spring (of elastic constant k) used in the motor cylinder:

$$F_m = F_p - F_s \Rightarrow T = \frac{F_p - k x_m}{F_p} \quad \text{Equation 3}$$

Several characteristics of the cylinder coupling actuation principle are essentially related to medical imaging compatibility:

(a) The scheme allows for the operation of the motor cylinder from a remotely located pump cylinder. This allows the motor located in the imaging field to be operated from a pump located in a control room.

(b) The simplicity of the motor allows for its construction of imaging environment compatible materials. The fluid agent used is also nonrestrictive.

(c) The motion of the motor rod can be predicted by measuring motion at the pump. Accuracy of measurement is increased by using hydraulic agent (incompressible) and low expandability circuitry. This eliminates the need of performing complicated motion encoding in close proximity of the imaging field.

These characteristics show that this remote actuation principle is well suited for performing linear motion actuation in a medical imaging environment. The method may also be extrapolated for rotary motion, as presented next.

Rotational output may be achieved by using at least three coupled pistons or cylinders engaging an elliptical shaft as presented in FIG. 2. In this schematic three sets of cylinders 3-6, 4-7, and 5-8 are linearly coupled as presented in the previous section. The cylinders are equally spaced around the elliptical cams 1 and 2 of the pump 60 and motor 70 respectively. Rotating the cam 1 of the pump causes the pistons 3, 4, and 5 to move, engaging their coupled pistons 6, 7, and 8 respectively, thus turning the motor cam 2. In this way, the pump and the motor shafts are coupled, so that ideally their rotation angles are equal $\Theta_m = \Theta_p$. Proper design of the cams and cylinder sizes ensure that the volume in the hydraulic circuits remains constant for any pump Θ_p and motor Θ_m rotation angles.

As for the cylinder coupling for linear motion, an incompressible fluid is required in order to achieve high accuracy of motion since rotational precision is directly related to the linear precision of the pistons. A low compressibility fluid is also required for high speed operation. This also allows for performing remote measurement of the motor shaft rotation using a pump encoder.

A stepper pneumatic motor could be achieved by replacing the pump arrangement presented in FIG. 2 with a simple pneumatic source and distributor that successively pulse pressurizes the three pistons of the motor, much like a radial engine used in old propeller airplanes.

The cam pump presented in FIG. 2 can also be replaced by (at least) three cylinders operated independently by linear drives such as voice coils. These should be synchronized and optimized for maximum dynamic performance under computer control.

In all cases, tight seal cylinders should be used since agent leakage would degrade kinematic performance. For this reason the use of diaphragm cylinders is recommended over the piston type. Diaphragm cylinders are also suitable since the stroke required is relatively small and such cylinders can be easily made of medical imaging compatible materials.

Remote position sensing can also be achieved with this coupling principle. For a theoretically zero driven torque, the pump and motor rotations are in phase. The phase shift Φ depends on the load connected to the motor shaft. This can be quantified by monitoring line pressures (P_1, P_2, P_3, K) and then used to evaluate the phase shift, thus:

$$\Theta_m = \Theta_p - \Phi(P_1, P_2, P_3, K) \quad \text{Equation 4}$$

This is essentially important for applications in which encoding of the motor shaft is not feasible or difficult to implement, as for medical imaging environment applications.

The disadvantage of this principle is related to the sliding of the piston ends on the elliptical cams during motion, which induces sliding friction at the contact surfaces thus reducing mechanical performance and causing wear. Design implementations of this principle require the inclusion of either rollers 9 at the end of the pistons or preferably a series of ball bearings 10 mounted on the perimeter of the cam. See FIGS 3A and 3B.

A harmonic drive transmission is a rotational – rotational transmission implementing torque coupling with concentric elements. A radial, rather than a rotation, tooth mesh is created by flexing one element to create an inward and outward, radial tooth motion, which allows a spline-like tooth engagement.

A harmonic drive transmission's precision and efficiency make it suitable for accurate positioning and precise motion control. The basic principle of the harmonic drive is illustrated in FIG. 4. It presents three basic elements: A rigid circular spline or the internal gear **11**, a flexspline represented by the thin gear **12**, and an elliptical wave generator **13** which is surrounded by a ball bearing **10** having inner **10a** and outer **10b** races. Commonly, the input is applied to the wave generator **13**. The output is either the circular spline **11**, as represented in FIG. 4, in which the flexspline **12** and the generator **13** are grounded, or vice versa (**11** grounded and **12** output).

The circular spline **11** has an even number of internal teeth (N_s), is circular, and rigid. The flexspline **12** also presents an even number of teeth (N_f), but fewer than the spline (typically $N_f = N_s - 2$), presents a thin cross-section, and is constructed of flexible materials so that it can be deformed to an oval shape by the wave generator **13**. The wave generator is an elliptical bearing presenting a major axis **14** and a minor axis **15**. The teeth engage at the major axis and are fully disengaged at the minor axis. The flexspline **12** is deformed by the bearing **10** to an elliptical shape changing its orientation with the rotation of the inner ring of the bearing, the drive input, thus rotating the axes of the ellipse. This causes the gear engagement region to rotate in phase with the input. Since the flexspline **12** has ($N_s - N_f$) fewer teeth than the circular spline **11**, one revolution of the input causes a relative motion of $N_s - N_f$ teeth between them. For the common case of two teeth difference, the output rotates one tooth-arc for each 180° of input rotation. In general, the transmission ratio of the harmonic drive can be expressed as:

$$T = \frac{\omega_w}{\omega_s} = \frac{N_s}{N_s - N_f} \quad \text{Equation 5}$$

If the spline **11** is considered the base, the direction of the output ω_s is reversed with respect to the input ω_w .

Equation 5 shows that the harmonic drive exhibits high transmission ratios from 50:1 and up. Preload in the direction of the major axis and almost pure radial

1 tooth engagement allow harmonic drives to operate with low or zero backlash for
2 long duty cycles, without preload adjustments or significant wear. Reliability and life
3 are also high. Since torque is transmitted by pure coupling, the efficiency of the
4 transmission is normally in the 80-90% range. The gearing design ensures that
5 approximately 10% of the total teeth are engaged at any rotation, minimizing the
6 effect of tooth-to-tooth error, thus rendering excellent positioning accuracy and
7 repeatability.

8 The above characteristics make the harmonic drive an ideal candidate for
9 precision surgical robotics. In addition, the presence of the elliptical wave generator
10 **13** readily associates functionality with the elliptical coupling presented above,
11 especially for the cam bearing case presented in FIG. 3B.

12 One embodiment of the present invention merges the principles of elliptical
13 coupling and harmonic drive by using cylinder couplings to actuate a wave generator
14 or actuator to act as what is herein referred to as a harmonic motor. A first
15 embodiment is shown in FIG. 5.

16 Pistons **6**, **7**, and **8** act on the outer race of the bearing **10**, similar to the
17 principle presented in FIG. 3B. The wave generator **13** is rotated by sequential
18 pulsing of the pistons, either by using an elliptical pump arrangement or by pumps
19 actuated independently. A set of mirrored cylinders may also be respectively
20 connected on the same fluid circuits for reducing radial load.

21 The main difference compared to the harmonic drive disclosed herein is that
22 the input energy is given by the fluid of the pistons and not a rotational input, thus
23 rendering a rotary motor rather than a transmission. The motor inherits the
24 mechanical performance of the cylinder coupling and harmonic drive, making it
25 optimally suited for precision actuation and medical imaging compatibility.

26 The harmonic motor is also safe to use in surgical applications, especially
27 when driven by a hydraulic agent such as distilled water or even saline. All hydraulic
28 circuits are closed and can be made leak proof by using diaphragm cylinders. The
29 fluid pulses back and forth in the circuits and the system may be operated at low
30 pressures. Should a hydraulic circuit fail, the motor stalls. Moreover, the drive can
31 be made backlash free and it is non-backdrivable if the pump is non-backdrivable.

Another embodiment of the present invention, the “static wave actuator version of the harmonic motor,” presents simpler construction and minimizes the number of moving elements by replacing the elliptical bearing 10 with an arrangement of cylinders which act as a active wave generator. The flexspline remains fixed but its oval shape is dynamically driven by cylinder couplings. Two types of wave actuators are defined based on the direction that the cylinders act, radial and tangential.

FIG. 6 presents a schematic of the radial wave actuator and the flexspline 12. For simplicity the rigid, circular spline 11 has not been represented in this schematic being similar to the one represented in FIG. 5.

The radial wave actuator comprises a flexible outer ring 19, a series of at least six diaphragm cylinders 6, 7, 8, 16, 17, 18 and a rigid cylinder ring 20 or platform. The flexspline 12 and the outer ring 19 are assembled or even constructed of in single part. Pairs of opposite cylinders are linked on the same fluid circuits connecting the radial wave actuator to a sequential pump through the ports 21, 22, and 23.

In unpressurized state the flexspline – outer ring assembly exhibits circular shape concentric with the cylinder ring 20. When pressure is applied in a circuit the flexspline 12 is deformed along the direction of the pressurized cylinders causing the gear teeth to engage in that direction. FIG. 6 represents the wave actuator pressurized in port 21 inducing an oval shape spline with 14 and 15 as major and minor axes respectively.

The other two circuits rotate the major elliptical axis to their respective directions. The three 120° spaced axes of the cylinders are *primary axes* and their number directly determines the precision of motion. However, increasing the number of the cylinder pairs has practical limitations and significantly increases complexity.

The following method allows for doubling the number of axes for the same number of cylinders. The method is based on the observation that if a thin ring is pushed from inside out on opposite sides, it deforms aligning the major axis in that direction. But if the ring is squeezed in the same places, the major axis is reversed 180°. Thus, by pulling the diaphragms inward (rather than pushing outward) a new set of *secondary axes* is created normal to the primary ones, as represented in FIG. 6.

To avoid operating below the atmospheric pressure (for pulling), the diaphragms are preloaded so that in unpressurized state they exert elastic pull on the outer ring **19**. This shifts the operating point above atmospheric pressure in a similar way that spring return pistons operate. This simple method uses the elasticity of the diaphragm in place of the classic return spring. Reducing the pressure below the central operating point causes the flexspline to engage at the secondary axis.

By independently operating each circuit the major axis can be oriented along any of the primary and secondary axes. With careful design of the sequential pump, coupled operation of the cylinders can orient the ellipse in arbitrary orientations providing smooth and precise motion of the rigid spline output.

Diaphragm cylinders are well suited for this application not only for their leak proof operation but also for implementing the spring return. For this reason the diaphragm should be manufactured of materials with good elastic properties. Moreover, as it can be easily observed in the exaggerated oval shape of FIG. 6, during motion the piston and cylinder axes lose coaxially. Thus, compliant (elastic) diaphragms are also accommodating this misalignment.

A schematic of another embodiment of the present invention in the form of a tangential wave actuator with a flexspline **12** is presented in FIG. 7. For simplicity the rigid, circular spline **11** has not been represented being similar to the one represented in FIG. 5. The tangential wave actuator comprises a special flexible wave ring **24** and a series of twelve inflatable cylinders **25a-25l** (at least six inflatable cylinders are required). The flexspline **12** and the wave ring **24** are assembled so that relative tangential slipping is unrestricted at their points of contact. Pairs of four opposite cylinders are connected on the same fluid circuits connecting the actuator to a sequential pump through the ports **21**, **22**, and **23**.

The wave generator ring **24** has a special construction presenting twelve equally spaced lobes **24a-24l** attached to a thin and elastic inner structure or membrane **26**. Semi-cylindrical cavities **27a-27l** are created between adjacent lobes for placing the inflatable cylinders (pillows) **25a-25l**. The outer surface of the lobes is constructed of elliptical surface that matches the region at the major axis of the flexspline ellipse.

1 Actuated oval shape of rotating major **14** and minor **15** axes is induced by
2 sequentially pressurizing the inflatable cylinders **25a-25l**. When pressure is applied
3 to a circuit, opposite groups of inflatable pillows expand enlarging the gap between
4 adjacent lobes. This deforms the wave generator ring to an oval shape with the major
5 axis aligned in the direction of the pressurized axis. The orientation of the major axis
6 is then rotated by sequential and coupled operation of the three circuits.

7 A hollow shaft cylindrical construction is common for the harmonic motor of
8 the present invention. This allows for mounting and/or passing the fluid circuit
9 tubing for the inflatable cylinders through the inside of the motor.

10 In a prototype version of a harmonic motor with a tangential wave actuator,
11 the rigid spline **11**, the flexspline **12**, and the wave generator **24** are constructed of
12 plastic materials. The inflatable cylinders **25** are silicone rubber tubes with closed
13 ends, which have been connected in three groups of circuits using 1/8" ID PVC
14 tubing. The harmonic drive using a 100 teeth rigid spline and a 98 teeth flexspline
15 implements a 50:1 transmission. The motor presents a hollow shaft, cylindrical
16 shape. The overall size of the motor is 60 mm x 25 mm with a 25 mm bore and it
17 weighs only 50g.

18 Prototype versions of the present invention's harmonic motors have been
19 thoroughly tested to ensure that they are compatible with a wide range of medical
20 imaging environments. These motors have proven themselves to be the first Zone 1
21 multi-imager compatible motors. That is, the motor can precisely operate within the
22 imager field of any known class of imaging equipment while the imager is acquiring
23 images. This includes the class of MR imagers for which all existing types of motors
24 (electric, piezoelectric, ultrasonic) are either incompatible or can not be set in close
25 proximity of the magnetic field, operational or not. All previously reported MRI
26 compatible robots inhabit MRI Zone 4 (one meter from iso-center or beyond the 20
27 mTesla line) and, in consequence, have limited manipulation ability within Zones 1
28 and 2.

29 FIGS. 8 - 9 show another of the preferred embodiments of the present
30 invention. This embodiment is referred to herein as a harmonic planetary motor.
31 It uses pneumatic/hydraulic pressure pulses to generate precise, backlash-free rotary

1 motion.

2 As shown in the side and sectional views of FIGS. 8A and 8B, the central part
3 of this embodiment is a cylinder body **29** presenting three radial cylinders **30**. Three
4 diaphragm **31** pistons **32** having top action surfaces **32a** are attached to the cylinder
5 body with the cylinder caps **33**. Each cylinder is pressurized through a nozzle **34**
6 linked to a port **35**. The pistons are attached with the screws **36** to a rigid planetary
7 gear **37** engaging an internal or wave generator gear **38**.

8 The outer surface **39** of the wave generator gear **38** is elliptical acting as a
9 wave generator for the next motion stage, the harmonic transmission. A ring bearing
10 **40** with rollers **41** and a cage **42** acts between the outer surface **39** of the gear **38** and
11 the inner surface **43** of the flexspline **12**. The rigid spline **11** is attached to the case **44**
12 of the module. The output of the motor is taken from the flexspline **12** through a
13 passive spline **45** presenting an internal rigid spline.

14 This motor operates by fluid pressure being sequentially applied on the three
15 diaphragm pistons **32** using a remotely located pneumatic/hydraulic commutation
16 mechanism. This engages the planetary gear **37** in a coupled motion around the
17 cylinder body **29**, thus engaging the rigid wave generator gear **38**. The planetary gear
18 **37** does not rotate but rather balances on a round trajectory around the cylinder **29** in a
19 quasi-translational motion, its rotation being prevented by the diaphragm **31**
20 connections to the cylinder base **29**.

21 For each full pressure cycle the wave generator gear **38** rotates with one tooth
22 angle, assuming that the difference in the number of teeth in the planetary and wave
23 generator gears is one. This rotation is further demultiplied through the combined
24 action of the surrounding flexspline **12** and spline **11** so that the output of the module
25 rotates through a spline tooth angle for each half turn of the wave generator **38**,
26 assuming that the difference in the number of teeth between the spline and flexspline
27 two.

28 This motor assembly is constructed of nonmagnetic and dielectric materials
29 such as mica-glass and toughened zirconia ceramics, polyimide plastics, and Buna-N
30 rubber. Six small custom-made titanium screws **36** are also used.

The planetary gear **37** in this assembly is constructed such that it has one more tooth than the wave generator gear **38**. Thus when the perimeter of the planetary gear **37** is caused to effectively walk the contact point with the wave generator's inner surface for a complete 360 degree revolution, the wave generator will advance through an angular rotation that is equal to 360 degrees divided by the number of teeth in the wave generator.

In this situation we have a harmonic planetary motor that acts to rotate a harmonic drive gear consisting of the circular spline **11**, flexspline **12**, and a wave generator **38**. One of the advantages of this configuration is the higher degree of precision that can be obtained in controlling the angular output that is experienced in the rotation of the flexspline. The magnitude of the output is seen to be:

$$\alpha_{OUT}^{360} = \frac{360}{N_{WG}} \frac{(N_{RS} - N_{FS})}{N_{RS}} \text{ degrees}$$

where, $N_{WG}, N_{PG}, N_{RS}, N_{FS}, N_{PS}$ are the number of teeth for the wave generator **38**, planetary gear **37**, rigid spline **11**, flex-spline **12**, and a passive spline respectively, and where:

$$N_{WG} = N_{PG} - 1$$

$$N_{RS} = N_{FS} + 2$$

$$N_{PS} = N_{FS}$$

FIG. 9 shows an illustration of the pump that is used to drive the harmonic motor of the present invention. In this situation, a pressure commutation mechanism is provided by three computer-controlled, proportional pneumatic valves generating a sequence of three sinusoidal waves of 120° phase shift. Such hydraulic actuation is capable of higher speed performance due to the incompressibility of the agent, and is also safer for surgical applications. The pump **46** comprises a cam **47** of cylindrical outer surface eccentrically mounted on a rotating shaft activated by the electric motor **48** through a bevel gear transmission. The inner part **49** of the cam presents a special shape (somewhat elliptical) so that two rollers **50** and **51** can simultaneously roll on

1 the inner and outer sides of the cam implementing a dual acting (push-pull) piston
 2 stroke. The rotation of the cam causes the pistons of the three cylinders **52** to move in
 3 an eccentrically coupled phase, as required for the planetary motor. The pressure
 4 waves are then sent to the motor through the ports **53**.

5 The motor of the present invention is also safe to use for medical applications
 6 since it is electricity free and presents a small size making it readily applicable for the
 7 construction of image-guided robots to operate within the confined space of various
 8 imagers, including closed bore tunnel types. This technology could potentially have a
 9 broad impact on the development of new image-guided motorized systems that could
 10 open new capabilities for diagnosis and treatment of prostate cancer and other
 11 diseases.

12 For example, this motor can be used for the construction of a multi-imager
 13 compatible robot for precise prostate access. Presently, prostate access for biopsy or
 14 therapy delivery can only be accomplished manually with or without the aid of
 15 template-like devices. A manual approach has intrinsic inaccuracies and is associated
 16 with variability among individual surgeons. A mechanism to precisely, repetitively,
 17 and reliably access the prostate is required to improve clinical outcome of classic
 18 procedures (i.e. biopsy, brachytherapy) and to create a basis upon which novel cancer
 19 therapies could be deployed and evaluated.

20 FIGS. 10A – 10B show another of the preferred embodiments of the present
 21 invention. This embodiment is referred to herein as a planetary motor. It uses
 22 pneumatic/hydraulic pressure pulses to generate precise, backlash-free rotary
 23 motion. This motor differs from the previously described harmonic planetary motor
 24 by its exclusion of the harmonic transmission stage and the improved design of the
 25 planetary gear of the present embodiment.

26 As shown in the side and sectional views of FIGS. 10A and 10B, the central
 27 part of this embodiment is a cylinder body **29** presenting three radial cylinders **30**.
 28 Three diaphragm **31** pistons **32** are attached to the cylinder body with cylinder caps
 29 **33**. Each cylinder **30** is pressurized through a nozzle **34** linked to a port **35**. The
 30 pistons **32** are attached with titanium screws **36** to a rigid planetary gear **37** engaging
 31 a ceramic internal gear **38a** which, in this embodiment, is the output of this motor.

1 A cylindrical needle bearing **40** with ceramic rollers **41** and a plastic cage **42**
2 supports the internal ceramic gear **38** within the ceramic case **44**. The motor is
3 powered by a hydraulic commutation pump **46** similar to the one previously
4 described, fluid pressure waves being sequentially applied on the three cylinders.
5 These act on the pistons **32** and the planetary gear **37** in a coupled motion about the
6 cylinder body **29** thus engaging the internal gear **38a**. The planetary gear **37** does not
7 rotate but translates on a circular trajectory about the cylinder body **29**. The gear **38a**
8 advances one tooth on each pressure cycle.

9 Although the foregoing disclosure relates to preferred embodiments of the
10 invention, it is understood that these details have been given for the purposes of
11 clarification only. Various changes and modifications of the invention will be
12 apparent, to one having ordinary skill in the art, without departing from the spirit and
13 scope of the invention.
14